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Advanced FT-IR high-speed spectrometer showing the feasibility of high performance optical MEMS based mid-IR sensing

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Abstract

We show latest results on the feasibility of miniaturized high performance FT-IR spectroscopic sensing. The concept of using micro-mirrors in FT-IR spectrometers has been put into practice combining novel MEMS micro-mirror devices with outstanding oscillation amplitudes, a miniaturised high-power IR source and a dedicated TE cooled MCT detector. The result is the first practically applicable prototype of a MEMS-based high-speed FT-IR spectrometer operable under real-world conditions. Covering the range 4000–700 cm⁻¹ (1.8–14 μm) at a spectral resolution < 10 cm⁻¹ and a maximal time resolution of 1 ms, it could provide a platform for a new generation of mid-IR sensors

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Keywords: MOEMS; translatable micro mirror; FT-IR; spectrometer; Michelson interferometer; MIR; mid-IR

1. Introduction

Standard FT-IR spectrometers are large, usually static, cost intensive and require operation by qualified personnel. The presented development involves achievements in MEMS technologies and electronics design to address size, speed and power requirements and develop a fully integrated miniaturized FT-IR

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spectrometer. A suitably matched interaction of multiple new components - source, interferometer, detector and control and data processing - develops unique MEMS based spectrometers capable of reliable operation and finally results in compact, robust and economical analyzers. An early prototype already drafted the road to a MEMS based mid-IR spectrometer [1] but appropriate detection limits and spectral quality standards for the application in analysis could not be met. The presented system now aims at a high performance level to measure in the range between $4000\text{--}700\text{ cm}^{-1}$ at a spectral resolution better than 10 cm^{-1} .

2. Prototype setup

A novel translatable MEMS mirror was specially designed for this system [2]. The Michelson interferometer design and the desired *performance* put several demands on the MEMS device. Amongst these, a mirror travel of $\pm 500\text{ }\mu\text{m}$ and a minimal dynamic deformation of $< \lambda/10$ peak-to-peak in combination with a large mirror aperture of 5 mm were the most challenging goals.

The new MOEMS device consists of four symmetric pantograph suspensions in contrast to two bending beams used in a former MEMS design, where only $\pm 100\text{ }\mu\text{m}$ amplitude could be achieved [3]. As shown in fig. 1, the mirror plate is supported symmetrically by four pantograph suspensions. One single pantograph consists of six torsional springs connected by stiff levers.

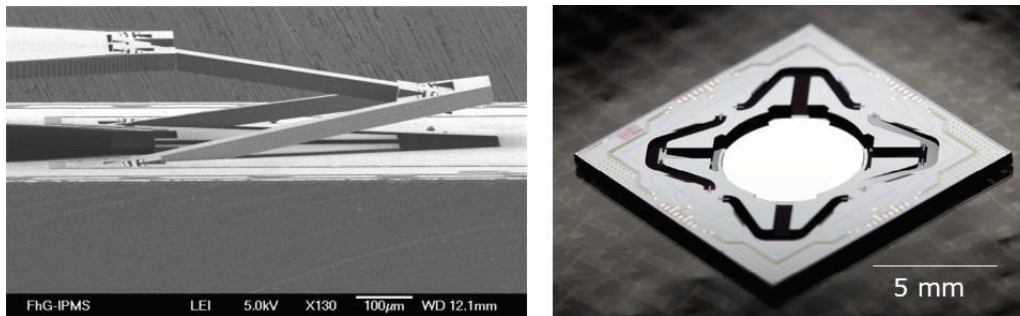


Fig. 1. SEM detail of a single pantograph structure at maximum deflection (left) and a photograph of the entire MEMS device with deflected mirror plate (right).

In addition to the mentioned specifications in terms of maximal mirror travel aperture and deformation of the mirror plate itself, the MEMS device has to suppress any parasitic oscillations, especially mirror tilts. This has been achieved by a consequent design-inherent mode separation of mirror plate and pantograph suspension structures. The first parasitic mode concerning a critical tilt of the mirror plate appears at a resonance frequency of 2238 Hz , which is well separated from the frequency of the desired piston mode at 500 Hz . To achieve a mirror travel of $\pm 500\text{ }\mu\text{m}$, the MEMS device has to be operated in reduced ambient pressure. Here, a preliminary version of a desired permanent optical vacuum package was used where the operating point in terms of pressure was set to 70 Pa . Applying an excitation voltage of 50 V , the optimal driving frequency was found at 930 Hz yielding a mirror oscillation at 465 Hz . Hence, a mirror travel of $\pm 380\text{ }\mu\text{m}$ could be achieved within this setup.

Besides the MEMS device as core element, further dedicated modules have been developed such as a thermoelectrically cooled MCT detector, covering the spectral range $2.5\text{--}14\text{ }\mu\text{m}$, so OH, NH and CH-stretch vibrations down to the fingerprint region can be observed. Heading for maximum throughput, a miniaturized IR source with an emission area of only $500\text{ }\mu\text{m}$ in diameter and narrow angular emission characteristics has been developed. Accounting for the maximal acceptable beam divergence, this allows the focal length of the collimating mirror to be set to 5.8 mm only, giving the highest possible numerical

aperture. AR coatings used for ZnSe beamsplitter and compensator window have been optimized for the desired wavelength range but also for a reasonable performance at the reference laser wavelength. It is shown in fig. 2 that compensator and IR window of the vacuum package coincide.

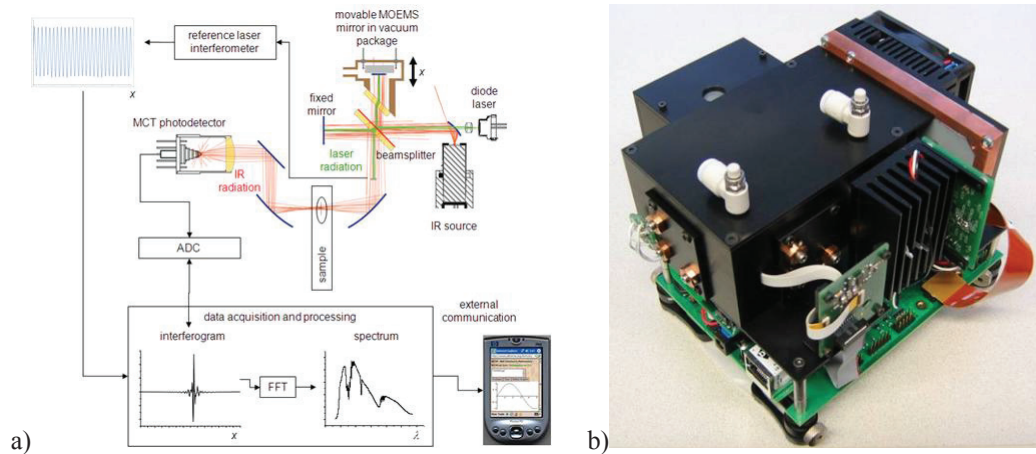


Fig. 2: a) Schematics of the layout and signal path of the FTIR system and b) photograph of the prototype system including IR source, interferometer, sampling chamber, detector, analog-to-digital converter, system and preprocessing electronics.

The optical set-up is based on a classical Michelson interferometer design with the MOEMS mirror as the key element. Fig. 2 shows the schematic layout and a photograph of the current prototype. With this stage a compromise between miniaturization and accessibility of all components was found. A later system could even be built more compact

For acquisition, a laser reference interferometer is implemented to enable equidistant sampling of the IR interferogram. In the context of this type of device with its harmonic motion, this method has been described previously [3]. Asymmetries in the interferometer setup itself, dispersion and electronic delays as well as residual parasitic modes and dynamic deformations of the MOEMS mirror cause small but observable differences in the sampled IR interferogram as the mirror travels forth or back. In order to exploit each scan, the reference interferometer not only encodes the absolute mirror position but also the actual moving direction. The direction signal detects the turning point of the MOEMS motion and thus triggers the acquisition (start/stop) of the actual scan. As the reference interferogram (after digitization) clocks the ADC, single scans can be precisely averaged and the quasi-harmonic motion of the MOEMS mirror is compensated.

Scanning times of 1 ms and a maximum sampling frequency of 2 MHz. puts high demands on system electronics. Thus, a flexible multiprocessor FPGA/DSP platform has been developed to cope with data acquisition, MOEMS and system control, calculation and communication tasks. A detailed description of the electronics has been published previously [4]. While the FPGA is used for real time processing tasks as data acquisition and MOEMS control, the DSP is used for computation intensive tasks and communications.

3. Results

Using the full capability of the MEMS mirror, the spectral resolution of the MOEMS FT-IR spectrometer is expected to reach 8 cm^{-1} in a final state. Currently, a mirror travel of $\pm 380 \text{ }\mu\text{m}$ is achieved and the interferogram is sampled symmetrically yielding a calculated spectral resolution of 13 cm^{-1} .

For spectral resolution characterization, transmission spectra of a clear 1.5 mil Polystyrene film have been obtained. In the spectrum, shown in fig. 4, all sample features in the order of 13 cm^{-1} are perfectly resolved, so the predicted resolution is confirmed experimentally.

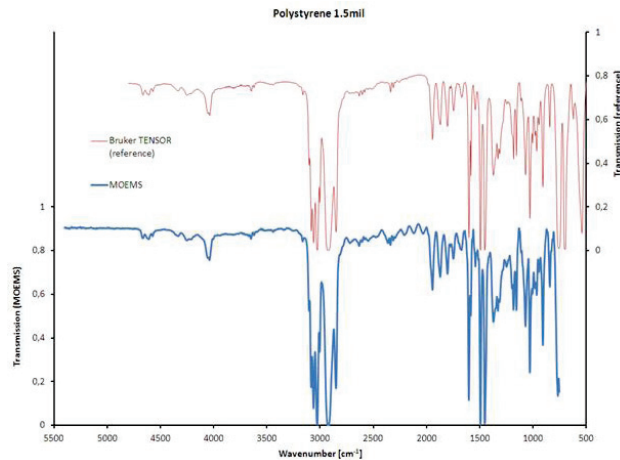


Fig. 3: Spectral accuracy and resolution characterization. Transmission spectrum obtained for certified polystyrene 1.5 mil reference with the MEMS spectrometer against the spectrum obtained with a Bruker TENSOR.

A single scan yields a S/N of 25:1; averaging of 1000 scans improves the S/N to 750:1 (peak-to-peak). However, resolution of $< 8\text{ cm}^{-1}$ and a SNR of 1000:1 is required to qualify a FT-IR system as a sensor for industrial applications e.g. process control. It is demonstrated that these specifications are almost met. Furthermore, due to the high scanning speed of about 1 ms, e.g. tracing of fast chemical reactions and transient states will also be addressed in future. Once a permanent vacuum package for the MOEMS device, as currently under development, is ready for integration the system will also get ready for mobile analysis, e.g., all-purpose hazardous vapor sensor, as a sensor for air- and spaceborne based IR analysis, etc.

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